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Time at the Beginning

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Abstract. Age consistency for the Universe today has been an important cosmological test. Even more powerful consistency tests at times as early as 10^{-32} sec lie ahead in the precision era of cosmology. I outline tests based upon cosmic microwave background (CMB) anisotropy, big-bang nucleosynthesis (BBN), particle dark matter, phase transitions, and inflation. The ultimate cosmic timescale – the fate of the Universe – will be in doubt until the mystery of the dark energy is unraveled.

1. Introduction

The cosmic clock ticks logarithmically. The Universe's past can be divided into three well defined epochs: the quantum era (10^{-42} sec to 10^{-22} sec); the quark era (10^{-22} sec to 10^{-2} sec); and the hot big-bang era (10^{-2} sec to 10^{17} sec). Earlier than the quantum era is the Planck era ($t < 10^{-42}$ sec); it holds the key to understanding the birth of the Universe, but requires a quantum theory of gravity to proceed. Just recently the Universe has entered a new era, of undetermined duration, where dark energy and its repulsive gravity are dominating the dynamics of the Universe (more later).

The third era derives its name from the very successful cosmological model that describes it; the important events include the synthesis of the light elements, the last scattering of radiation, the formation of large-scale structure and the onset of accelerated expansion. The earlier two eras are still largely terra incognita, though we have some tantalizing ideas: the transition from quark/gluon plasma to hadronic matter, the electroweak phase transition, and the birth of particle dark matter during the quark era; and inflation and the origin of the matter – antimatter asymmetry during the quantum era (see Figure).

There is no doubt that cosmology is in the midst of the most exciting period ever. Progress in understanding the origin and evolution of the Universe is proceeding at a stunning pace. I mention a few of the highlights of the past decade: COBE discovery of the small density inhomogeneities ($\delta\rho/\rho \sim 10^{-5}$) that seeded large-scale structure, the mapping of CMB anisotropy on scales down to 0.1 degree and the determination of the shape of the Universe

(flat!), identification of the epoch of galaxy formation, determination of the Hubble parameter to a precision of 10%, and the discovery of cosmic accelerated expansion.

There is much more to come. These recent discoveries and those still to be made will test the framework of the standard cosmology and begin to open the quark and quantum eras. We are already on the way to establishing a new standard cosmology: a flat Universe comprised of 2/3rds dark energy and 1/3rd dark matter that is accelerating today and whose seeds for structure came from quantum fluctuations stretched to astrophysical size during inflation. Much remains to be done to put the new cosmology on the same firm footing as the hot big-bang model; much of cosmology over the next two decades will be devoted to this (see e.g., Turner, 2001a).

The richness and redundancy of the measurements to be made will also allow a number of consistency tests of the big-bang framework and its theoretical foundation, general relativity. Many of these tests involve cosmic timescales, and that is the subject of my talk.

2. $H_0 t_0$: “Sandage Consistency Test”

The product of the present age and Hubble constant is a powerful consistency test. The standard hot big bang has not always cleared this hurdle, cf. the late 1940s when the Hubble age of about 2 billion years fell short of the age of the solar system by a factor of two (see e.g., Kragh, 1996) or the more recent scares when some measurements of H_0 and t_0 drifted upward.

Recognizing the importance of age consistency, Sandage has devoted much of his career to measuring the Hubble constant H_0 and independent indicators of the age of the Universe (and pioneered many of the methods); hence the title of this section.

The nature of the test has changed over Sandage’s career; the importance has not. Until recently one would have written $H_0 t_0$ in terms of one parameter, Ω_M , the fraction of critical density in matter, also assumed to be the total fraction of critical density contributed by all forms of matter and energy ($\equiv \Omega_0$). The discovery of accelerated expansion increased the number of parameters to two, Ω_M and Ω_Λ (fraction of critical density in a cosmological constant; $\Omega_0 = \Omega_M + \Omega_\Lambda$). The realization that accelerated expansion is here to stay, while the cosmological constant may not, added another parameter, $w = p_X/\rho_X$ (the equation-of-state of the dark energy) (see below). The determination from CMB anisotropy measurements that the Universe is flat, effectively reduced the number of parameters to two, Ω_M and w :

$$\begin{aligned}
 H_0 t_0 &= f(\Omega_0) && \rightarrow 1998 \\
 &= f(\Omega_M, \Omega_\Lambda) && 1998 \rightarrow 1999 \\
 &= f(\Omega_M, \Omega_X, w) && 1999 \rightarrow 2000 \\
 &= f(\Omega_M, w) && 2000 \rightarrow ? \\
 &= f(w) && ? \rightarrow ?
 \end{aligned}$$

For the first two cases, there are well known analytic formulae for f ; for the others there are not.

There is hope, that in the next ten years Ω_M will be pinned down by a combination of CMB, cluster and large-scale structure measurements, reducing the number of parameters to one again. At the moment, my analysis of this data gives, $\Omega_M = 0.33 \pm 0.035$ (Turner, 2001b), and I believe there will be significant improvement over the next decade.

The function f that accounts for the effect of slowing/speeding up on the age of the Universe is given by (for a coasting universe $f = 1$):

$$f \equiv H_0 t_0 = \int_0^\infty \frac{dz}{(1+z)H(z)/H_0}$$

$$H(z)/H_0 = \left[\Omega_M(1+z)^3 + \Omega_X(1+z)^{3(1+w)} + (1-\Omega_0)(1+z)^2 \right]^{1/2} \quad (1)$$

where the small contribution from the CMB and relativistic neutrinos ($\Omega_R \sim 10^{-4}$) has been neglected and w has been assumed to be constant.

To illustrate the status of this test, for H_0 and t_0 I will use the values reported at this meeting, $H_0 = 72 \pm 7 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ (Freedman, 2001) and $t_0 = 13.5 \pm 1.5 \text{ Gyr}$ (Chaboyer, 2001). This leads to

$$H_0 t_0 = 0.94 \pm 0.14$$

Taking $\Omega_0 = 1$ and $\Omega_M \simeq 0.35$, this is consistent with $w < -\frac{1}{3}$ (at 1σ) – the new cosmology passes the Sandage consistency test with flying colors! While not a tight constraint on w , it does provides more evidence for dark energy (i.e., a smooth component with large, negative pressure): if the dark energy were pressureless ($w = 0$), then $H_0 t_0 = 2/3$, which is clearly inconsistent with current data.

At present, the Sandage test has a precision of about 15%; what kind of improvement could one hope for over the next decade. Together, physics-based measures of H_0 (especially the CMB) and distance scale measures might well pin down the Hubble constant to a few percent. However, it is difficult to imagine independent measures of the age achieving similar accuracy. One irreducible uncertainty for all methods, is the time to formation (of stars, globular clusters, white dwarfs, etc). Reducing this uncertainty to 0.5 Gyr would still leave a 5% uncertainty in $H_0 t_0$. As I will discuss, other tests of age consistency, at much earlier times, are likely to be significantly more precise.

2.1. Mapping the expansion rate

The expansion rate at any epoch is related to the age of the Universe. For example: during a matter-dominated epoch, the scale factor $R(t) \propto t^{2/3}$ and $t = 2/3H(t)$; and during a radiation-dominated epoch $R(t) \propto t^{1/2}$ and $t = 1/2H(t)$. The expansion rate is more accessible than the age at early times.

The expansion rate determines a key observable: the comoving distance to an object a redshift z ,

$$H_0 r(z) = \int_0^z \frac{dz}{H(z)/H_0} \quad (2)$$

where a flat Universe has been assumed. The cosmological volume element, luminosity distance and angular-diameter distance are all directly related to

$r(z)$

$$\begin{aligned} dV/dz d\Omega &= r(z)^2/H(z) \\ d_L &= (1+z)r(z) \\ d_A &= r(z)/(1+z) \end{aligned}$$

A number of probes of the expansion history from $z = 0$ to $z \sim 2$ have been discussed recently. They include gathering a large sample of type Ia supernovae (SNAP) and counting halos or clusters of galaxies. From these “experiments,” individually or taken together, one could imagine mapping out $H(z)$ back to redshift $z \sim 2$ (see e.g., Huterer & Turner, 2000; or Tegmark, 2001). Note that the volume element and luminosity distance taken together, can in principle directly yield $H(z)$.

Loeb (1998) has gone one step further, suggesting ultra-precise redshift measurements of the Lyman-alpha forest over a decade or more could be used to determine $H(z)$ directly(!). The idea is to measure the tiny time variation of the redshifts of thousands of Lyman-alpha clouds,

$$\begin{aligned} \delta z &= [-H(z_1) + (1+z_1)H_0]\delta t \\ &\sim 0.2(\delta t/10 \text{ yrs}) \text{ m sec}^{-1} \quad \text{for } z = 3 \end{aligned} \quad (3)$$

where δt is the time interval of the observations. Whether or not this bold idea can be carried out remains to be seen, but it certainly is exciting to think about.

3. CMB anisotropy and acoustic peaks

As is now very familiar, the power spectrum (in multipole space) of CMB anisotropy arises due to acoustic oscillations in the baryon – photon fluid around the time of last scattering (see e.g., Hu et al, 1997). At this time, the baryons (and electrons) are falling into the dark-matter potential wells; still coupled to photons (through Thomson scattering off electrons), the infall is resisted by photon pressure and oscillations ensue. At maximum compression the photons are heated and at maximum rarefaction they are cooled.

The CMB is a snapshot of the Universe at 400,000 yrs; regions caught at maximum compression (rarefaction) lead to hot (cold) spots on the microwave sky. While the physics is most easily explained in real space, the signal is best seen in multipole space, as a series of peaks and valleys. The power at multipole l is largely due to k -modes satisfying: $k \sim lH_0$

The condition for maxima in the power spectrum is: $\omega_n t_{\text{LS}}/\sqrt{3} = n\pi$, where $n = 1, 2, 3 \dots$; the odd peaks are compression peaks and the even peaks are rarefaction peaks, $\omega = (1+z_{\text{LS}})k$ is the physical oscillation frequency at the time of last scattering, and $t_{\text{LS}} \simeq 400,000$ yrs is the age of the Universe then. Thus, in a flat Universe, the harmonic peaks occur at multipoles

$$l_n \sim \frac{n\pi}{H_0 t_{\text{LS}}(1+z_{\text{LS}})} \sim 200n$$

While the above formulae are approximate, they capture the physics. In particular, that the positions of the peaks depends upon the age of the Universe at last scattering. There will be sufficient redundancy in the information

encoded in the 3000 or so multipole amplitudes that will be measured to not only determine cosmological parameters, but also to check the consistency of the standard relationship between age and energy density.

In particular, an analysis by Lopez et al (1999) has projected that the Planck mission will be able to peg the neutrino contribution to the energy density of the Universe at last scattering to about 1%. The expansion rate is related to the energy density, $H^2 = 8\pi G\rho/3$, and neutrinos contribute about 1/5th of the total energy density at the time of last scattering. A quick estimate from Lopez et al (1999) indicates that ultimately, CMB anisotropy will provide an age consistency test at about 0.1% precision, 400,000 yrs after the beginning.

The limitations of this test should be noted however. Actually determining the age of the Universe at last scattering, whose redshift is readily determined by thermodynamic considerations ($1 + z_{\text{LS}} \simeq 1100$), is pegged to the present Hubble constant, $t_{\text{LS}} \simeq H_0^{-1}/[\Omega_M(1 + z_{\text{LS}})^{3/2}]$, and thus can be no more accurate than the age of the Universe itself. The CMB consistency above actually probes the relationship between expansion rate and the energy density of the Universe, a test of the big-bang framework and general relativity.

4. Big-bang Nucleosynthesis

Big-bang nucleosynthesis (BBN) is a cosmological experiment of great importance. In essence, it is a quenched nuclear reactor whose by-products are the primeval mix from which the first generation stars were born.

The expansion rate of the Universe controls the quench rate: $|\dot{T}/T| = H$. The yields of D, ^3He , ^4He and ^7Li , the primary products of BBN, are sensitive to the quench rate, and thus to the expansion rate

$$\frac{\delta X}{X} \sim \frac{\delta H}{H_{\text{STD}}} \quad (4)$$

where the coefficient of proportionality varies from about 1.5 for ^7Li to about 0.6 for ^4He .

Measurements of the primeval deuterium abundance (see e.g., O'Meara et al, 2001) together with predictions for its BBN yield pin down the baryon density, $\Omega_B h^2 = 0.02 \pm 0.001$ (Burles et al, 2001a). Using this value, the other light-element abundances can be predicted, e.g., $Y_P = 0.2472 \pm 0.0005$. Of the four light elements, the primeval ^4He abundance is known most accurately, $Y_P = 0.244 \pm 0.002$ (though there is still much debate about systematic error; see e.g., Burles et al, 2001b, or Olive et al, 2000).

The sensitivity of the ^4He abundance to the expansion rate is: $\delta Y_P = 0.15(\delta H/H_{\text{STD}})$. The current agreement of prediction with observation translates to a 2% test of the consistency of the big-bang prediction for the expansion rate around 1 sec, or about 5 times better than the Sandage test! With improved measurements of the baryon density, both from BBN and CMB anisotropy (see below), one might hope to see an improvement of a factor of five or so in the next decade.

Finally, as Carroll & Kaplinghat (2001) have recently emphasized, BBN can be discussed without reference to the standard cosmological model. The yields

can be analyzed completely in terms of the quench rate, $|\dot{T}/T|$, and nuclear input data with only the assumption of the Robertson – Walker line element (and not the Friedmann equations which relate the quench rate to the temperature). BBN not only offers a window on the very early Universe, but an almost model-independent timescale test.

5. CMB + BBN and the Baryon Density

Together, the CMB and BBN offer a remarkable test of the consistency of the standard cosmology and general relativity. As mentioned in the previous section, measurements of the primeval deuterium abundance together with precise theoretical predictions can be used to infer the baryon density:

$$\Omega_B(\text{BBN})h^2 = 0.02 \pm 0.001 \quad (5)$$

Since the first measurements of the primeval deuterium abundance in 1998, BBN has provided the best determination of the baryon density (see e.g., Schramm & Turner, 1998).

The CMB provides an independent measure of the baryon density based upon the physics of gravity-driven acoustic oscillations 400,000 yrs after BBN. Specifically, it is the ratio of the heights of the odd to even acoustic peaks that is sensitive to the baryon density (and insensitive to other cosmic parameters; see e.g., Hu et al, 1997). The ratio of the heights of the first and second peaks is

$$\frac{\text{peak}_1}{\text{peak}_2} \simeq 2 \left(\Omega_B h^2 / 0.02 \right)^{2/3} \quad (6)$$

where the peak heights are measured in microKelvin².

The Boomerang and Maxima experiments were the first CMB experiments to probe the first and second peaks (and to show that the Universe is flat; de Bernardis et al, 2000; Hanany et al, 2000); based upon their results a value for the baryon density was inferred (Jaffe et al, 2001)

$$\Omega_B h^2 = 0.032^{+0.005}_{-0.004}$$

While this baryon density is about 2σ higher than the BBN value, it confirmed a key prediction of BBN – a baryon density far below that of the best estimates of the total matter density ($\Omega_M \sim 0.3$ vs. $\Omega_B \sim 0.05$).

Only a couple of months after this meeting, Carlstrom's DASI experiment at the South Pole announced even more accurate and independent measurements of the first three acoustic peaks (Pryke et al, 2001) and arrived at a slightly lower baryon density:

$$\Omega_B(\text{CMB})h^2 = 0.022^{+0.004}_{-0.003} \quad (7)$$

which is bang on the BBN value! Boomerang analyzed more data and refined their beam map and pointing model and arrived at an identical value (Netterfield et al, 2001).

The agreement between these two numbers is stunning. Using the fact that $(\text{D}/\text{H})_P \simeq 3 \times 10^{-5} (\Omega_B h^2 / 0.02)^{-1.6}$ and the sensitivity of D/H to the expansion

rate,

$$\frac{\delta(D/H)}{(D/H)} \simeq 1.4 \frac{\delta H}{H_{\text{STD}}},$$

it follows that

$$\frac{\delta(\Omega_B h^2)}{\Omega_B h^2} \sim -0.9 \frac{\delta H}{H_{\text{STD}}}$$

Thus, the agreement of the BBN and CMB baryon densities checks the consistency of the standard expansion rate (at about 1 sec) to a precision of about 15%. Eventually, both determinations of the baryon density should achieve about 1% or so accuracy, and a factor of ten in the precision of this test might be expected.

6. Particle Relics

The evidence for particle dark matter has only gotten stronger: firmer evidence for $\Omega_B \ll \Omega_M$ (discussed above); the many successes of the CDM scenario of structure formation (and no viable model for structure formation without particle dark matter); the detection of acoustic peaks as predicted by inflation and CDM (Netterfield et al, 2001; Pryke et al, 2001); and growing circumstantial evidence for supersymmetry.

The most promising particle candidate is the lightest supersymmetric particle, which in most models is a neutralino of mass 100 to 300 GeV (see e.g., Jungman et al, 1996). Relic neutralinos remain numerous today because of the incompleteness of neutralino annihilations in the early Universe.

At temperatures when $kT \gg m_\chi c^2$, neutralinos and anti-neutralinos are present in numbers comparable to that of photons; as the temperature drops neutralinos must annihilate to maintain thermal abundance (a factor $e^{-m_\chi c^2/kT}$ less than that of photons). Eventually, annihilations cannot keep pace with the quench rate (the annihilation rate per neutralino, $\Gamma = n_\chi \langle \sigma v \rangle_{\text{ann}}$, falls rapidly as the neutralino abundance decreases exponentially) and the neutralino abundance “freezes out.” Freeze out occurs at a temperature, $kT_f \sim m_\chi c^2/30$, corresponding to a time of around 10^{-7} sec. The mass density contributed by relic neutralinos is given by

$$\Omega_\chi h^2 \propto \frac{H(kT \sim m_\chi c^2/30)}{\langle \sigma v \rangle_{\text{ANN}}} \quad (8)$$

While an approximation, this formula captures the essence of the neutralino production process (see e.g., Kolb & Turner, 1990).

Here is the future timescale test: $\Omega_\chi h^2$ will be measured by CMB anisotropy experiments to percent level precision. The properties of the neutralino can be measured at an accelerator lab (next linear collider?) to 10% precision (Brhlik et al, 2001). From this, the expansion rate at $kT = m_\chi c^2/30$ can be inferred and compared to the standard formula. (To be more precise, the measured properties of the neutralino and the Boltzmann equation in the expanding Universe can be used to predict the relic mass density and compared with the value inferred from CMB measurements.) If the neutralino is indeed the dark-matter particle (or another particle that can be produced in the lab), we can look forward to a 10% consistency test of the expansion rate at a time of less one microsecond!

7. Phase Transitions

If current ideas about particle physics are correct, then, during its earliest moments, the Universe should have gone through a series of phase transitions associated with symmetry breaking (e.g., QCD, electroweak, grand unification, compactification?). During a first-order phase transition, the Universe gets “shaken up” as bubbles of the new phase expand and collide. This can lead to the production of prodigious amounts of gravitational radiation, resulting in $\Omega_{\text{GW}} h^2 \sim 10^{-10}$ today. Laboratory-based knowledge of particle physics (e.g., for the electroweak phase transition, the mass of the Higgs boson) can be used to predict with precision the spectrum and amount of gravitational radiation (Kosowsky, Turner & Watkins, 1992); both depend directly upon the expansion rate at the temperature at which the phase transition takes place. If the stochastic background of gravitational waves from a phase transition can be detected and the particle physics independently probed in the laboratory a cosmological timescale test can be carried out at very early times (e.g., for the electroweak phase transition, $t \sim 10^{-11}$ sec).

8. Inflation

Inflation also produces gravitational waves, by a different mechanism – deSitter-space produced quantum fluctuations in the space-time metric. The stochastic background of gravity waves produced by inflation have wavelengths from 1 km to the beyond the size of the present horizon. Gravity waves are one of the three key predictions of inflation (together with a flat Universe and a nearly scale-invariant spectrum of adiabatic, Gaussian density perturbations; see e.g., Turner, 1997a).

Detection of gravitational waves, either by their imprint on CMB anisotropy and/or polarization or directly by a gravity-wave detector (LIGO?, LISA?), would not only confirm a key prediction of inflation, but would also reveal the timescale for inflation: The level of gravitational radiation produced by inflation is directly related to the expansion rate during inflation:

$$h_{\text{GW}} \sim H_I / m_{\text{Pl}}$$

Measuring the dimensionless metric strain h_{GW} gives the Hubble parameter during inflation in units of the Planck energy ($= 1.22 \times 10^{19}$ GeV). Further, if the spectrum of gravitational radiation can be probed, then there is a consistency test of inflation (and cosmology): $T/S = -5n_T$, where T (S) is the contribution of gravity waves (density perturbations) to the quadrupole CMB anisotropy, and n_T is the spectral index of the inflation-produced gravitational waves (Turner, 1997a,b).

As a practical matter, gravity waves from inflation can probably only be detected if $H_I > 3 \times 10^{12}$ GeV, corresponding to a timescale of $H_I^{-1} < 10^{-30}$ sec. Said another way, *if* gravity waves from inflation are detected we will be probing the Universe at a time at least as early as 10^{-30} sec.

9. Dark energy & destiny

For decades cosmologists have believed that geometry (or equivalently Ω_0) and the fate of the Universe were linked. The shape of the Universe has been determined through measurements of CMB anisotropy, $\Omega_0 = 1.0 \pm 0.04$ (Pryke et al, 2001; Netterfield et al, 2001; Hanany et al, 2001), but we are further away than ever from determining the destiny of the Universe. This is because 2/3rds of the critical density is in dark energy rather than matter, and the connection between geometry and destiny only applies when the Universe is comprised of matter (or more precisely, stress-energy with $p > -\rho/3$; see Krauss & Turner, 1999).

The discovery of accelerated expansion through type Ia supernovae distance measurements (see Tonry, 2001) was surprising, but can easily be accommodated within the framework of general relativity and the hot big-bang cosmology: In general relativity, the source of gravity is $\rho + 3p$, so that a fluid that is very elastic (negative pressure comparable in magnitude to energy density) has repulsive gravity. The simplest example is the quantum vacuum (mathematically equivalent to a cosmological constant), for which $p = -\rho$.

Unfortunately, all estimates of the energy of the quantum vacuum exceed by at least 55 orders-of-magnitude what is required to explain the acceleration of the Universe, suggesting to many that “nothing weighs nothing” and that something else with large negative pressure is causing the accelerated expansion (e.g., a rolling scalar field, aka as mini inflation or quintessence, or a frustrated network of cosmic defects; see Turner, 2000 or Carroll, 2001). Borrowing from Zwicky, I have coined the term “dark energy” to describe this stuff, which is clearly nonluminous and more “energy like” than “matter like” (since $|p|/\rho \sim 1$). It seems to be very smoothly distributed and its primary effect is on the expansion of the Universe. The first handle we will have in determining its nature is measuring its equation-of-state $w = p/\rho$ through cosmological observations (see e.g., Huterer & Turner, 2000).

Until we figure out the nature of the dark energy, the ultimate timescale question is on hold. Accepting that the Universe is flat (or at least that our bubble is; see Guth, 2001), the possibilities for destiny are wide open: continued accelerated expansion (and the almost complete “red out” of the extragalactic sky in 150 billion years) if the dark energy is vacuum energy; eternal slowing if the dark energy dissipates and matter takes over the dynamics; or even recollapse if the dark energy dissipates revealing a small, negative cosmological constant (Krauss & Turner, 1999).

10. Concluding Remarks

Cosmology is in the midst of a Golden Age (see e.g., Turner, 2001a). As this meeting has illustrated, other areas of astronomy have not been left behind either. Astronomy in general is in the midst of the most exciting period of discovery ever.

The enormous variety and range of timescales in astrophysics makes the subject rich. Cosmology provides an especially good illustration, because the cosmological clock ticks logarithmically. Consistency checks on the cosmological

clock have and will continue to play an important role in validating the standard cosmological model. While the consistency of the present age and expansion rate (Sandage test) is important and will improve in accuracy, from its present 15% to perhaps 5%, there are many other age consistency tests in cosmology, whose precision may well approach a few tenths of a percent (e.g., BBN and CMB), and extend to times as early as 10^{-30} sec.

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